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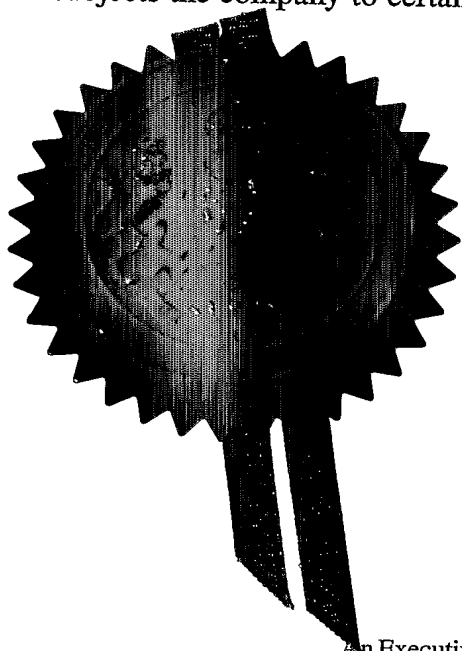
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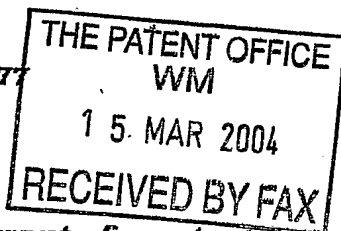
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0405773.3

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1... Limited

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08113870001

Patents ADP number (if you know it)

15 MAR 04 E881053-1 D10153

P01/7700 0-00-0405773.3 NONE

If the applicant is a corporate body, give the country/state of its incorporation

England

4. Title of the invention

AUTOFOCUS METHOD

5. Name of your agent (if you have one)

Uraula Lenel

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

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AUTOFOCUS PATENT -V4- - 15th March 2004

Inventors: David Richards, Tony Hooley, Jim Allan, Rob Leedham, Mark Shepherd

Background

Bringing a picture into sharp focus typically involves two (entirely) separate processes:

1. A process to measure the focus quality of an image (from here called a 'Figure of Merit' and symbolised as M)
2. A process to control an actuator (taking input from the first process) that in some way modifies the focus of the image onto the image sensor.

With regard to the first process (measurement of M):

Weintroub et al. [US Patent Application Publication number US2003/117514, *Method and Apparatus for Detecting Optimum Lens Focus Position*] describe a method for using an image compression system to determine the Figure of Merit M of an image. The principle is simple – a well focussed picture contains more information and therefore will not compress as well as a defocused image of the same scene. Therefore, a system which takes in a sequence of images with different focus adjustment can pick the one with the maximum compressed file size as the best focus position.

The reasoning that increased input information content directly corresponds to increased output file size is most true if a maximum entropy lossless coding has been used. Lossy image compression systems typically contain quantising elements which specifically discard, or reduce the number of bytes available to code, information relating to higher spatial frequency components.

Lossless compression methods which aspire to Maximum Entropy (for example LZW) may fall foul by encoding information which is not relevant for focus – for example in the case where there is a high level of pixel to pixel noise.

In either case there is an argument for some degree of image preprocessing, but not in the direction that is usually performed for image compression.

More specifically with respect to cameras and focussing, many elements of auto-focussing cameras are very well known. Auto-focussing (AF) camera systems have been described in broad terms many times. Fig.1 shows a general schematic representative of most of these AF schemes.

A focus controller moves a lens or lens group or lens-shape by means of a motor (which in this instance can be an actuator of any kind, including a lens with inherent variable focus length, such as a liquid-lens). The focus controller can take information to find the best focus position from one or more sources:

Distance estimation techniques (generally open-loop):



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- Ultrasonic range finder (using a *time-of-flight* calculation)
- Infra-red (using a *reflected luminance* \propto *distance*² calculation)

Image analysis:

- Splitting the optical path before the sensor and placing additional optical elements in the field of view, such as the shallow prisms or 'microscreens' found in SLR cameras. These can be analysed by a separate CCD
- Maximising high frequency content of an image (either optically or digitally)
- Other digital methods possibly using heuristics based on statistics derived from a processed image. (For example, entropy measures and conversely compressibility of pictures, histogram / saturated pixel count etc...)

The Focus Controller then applies some image-focussing algorithm or auto-focus algorithm, to the input information, to produce an output which is then used to control the focussing motor/actuator via a motor-driving-circuit.

A common way of describing an auto-focus algorithm is simply to say that '*one maximises the power in a high-pass filtered image*'. Typically this may be done in one of several ways:

1. Integrate the modulus of high-pass filtered data as it comes off the sensor (only gives you Figure of Merit in one dimension);
2. Take an image, convolve it with a high pass filter and find the power of the result;
3. Take an image (maybe split into blocks), then do some frequency domain transform (such as FFT / DCT) and apply a frequency domain filter and sum the power;

These all achieve the described effect, but they all behave very differently.

In the first embodiment of this invention approach 3 above is used – the image is DCT (Discrete Cosine Transform) transformed in 8x8 pixel blocks. The figure of merit *M* is constructed by multiplying each element of the DCT transformed image data by the frequency-filter coefficients, and then taking the sum of absolute values of the resultant (this is computationally cheaper than an RMS calculation and nearly as useful).

$$B_{n,m} = \sum_{j=0}^7 \sum_{i=0}^7 |D_{n,m}(i,j)F(i,j)|$$

$$M = \sum_{m=0}^{21} \sum_{n=0}^{17} B_{n,m}$$

Where

- $B_{n,m}$ is the Figure of Merit for block (n,m)
 M is the overall Figure of Merit
 $D_{n,m}$ is the transformed data of block (n,m)
 F are the coefficients of a frequency domain filter

(In this particular instance the numbers 21 and 17 arise from working on a QCIF resolution image but the method easily generalises to images of any shape and size, all of which are included in this invention)

The design of filter $F(i,j)$ is important. With the assumption that we can only work with the blocks that we are given at the output of the image sensor (i.e. not reconstruct the original



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image and do spatial processing on it), there are a few things we can say about the requirements for this filter:

- The DC coefficient must be zero as the DC signal never conveys useful focus information
- Very high frequencies are likely to be dominated by pixel noise (if this can be proved by analysis of the circle of confusion of a particular system, that would be very helpful information). These frequencies should also be attenuated.
- Intermediate frequencies will contain the useful focus information

The transition bands between these zones should not be too abrupt, otherwise they could act as a threshold, and prevent the algorithm working under some circumstances.

Designing frequency domain filters from spatial prototypes is one way to get satisfactory results. i.e. knowing what convolution operation is needed in the spatial domain, this can be transformed into a frequency domain multiplication.

A known (good) spatial edge-filter is the Laplacian of a Gaussian filter. The continuous version of this function is:

$$f(x, y) = \frac{(x^2 + y^2 - 2r^2)e^{-\frac{x^2 + y^2}{2r^2}}}{r^4}$$

Where:

$f(x, y)$ is the spatial domain filter (where x and y are spatial co-ordinates)
r is the radius of the Gaussian blur

The Laplacian is a differential operator which gives increasing gain with frequency. The Gaussian is a blur operation which rolls off the gain at high frequency. The advantage of this filter design is that it is easy to understand its operation in terms of spatial performance - the Gaussian blur radius is specified in pixels and is related to the size of the smallest detail that is believed to be "real" (and not noise) in the image.

A second appealing feature of this function is that it is circularly symmetric. If it is transformed by a DCT, then image components which correspond to asymmetric cosines must become zero (i.e. about 75% of the resulting coefficients). Additionally, the resulting coefficient matrix must be symmetric which potentially halves the number of multiplies to just 9. Furthermore, coefficients can be scaled such that they can be reasonably represented in the form 2^n (i.e. a shift operation in a binary digital processor), or some simple combination of a few shift and add operations.

A typical frequency domain filter (Gaussian radius = 1 pixel) generated by this method is:

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0	0	93	0	183	0	119	0
0	0	0	0	0	0	0	0
93	0	209	0	256	0	148	0
0	0	0	0	0	0	0	0
183	0	256	0	201	0	96	0
0	0	0	0	0	0	0	0
119	0	148	0	96	0	39	0
0	0	0	0	0	0	0	0

This method in its entirety produces quite satisfactory results - it compares well in simulation with other methods (some frequency based, some spatial based). Clearly, from the specific description given above, this process may be generalised to other similar but differently scaled circumstances, all of which form part of this invention.

Simply using JPEG file size of a compressed image as a Figure of Merit M , can work poorly, as the quantiser can be problematic - it can throw away the information wanted to determine sharp focus. The JPEG recommendation for luminance quantisation is as follows:

16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	103	NC

(NC Indicates this value is never coded)

As can be seen, the values close to DC have the lowest quantisation (and therefore represent the highest contribution to resulting file size), and higher frequencies are monotonically more coarsely encoded.

The JPEG standard allows the quantiser matrix to be freely chosen (although it is not a requirement that all compressor accept arbitrary quantisers). So, *in a second aspect of this invention* we adapt the quantiser matrix to pass through information deemed useful for focussing, and in one preferred implementation do this by making the quantiser table the reciprocal of the Laplacian of Gaussian filter presented above.

In this case, the resulting file size may be considered an accurate representation of total quantity of useful focus information.

To summarise this last point, the requirements of '*information for focussing*' and '*information for aesthetically pleasing viewing*' are somewhat in opposition. There is an advantage in



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adapting the loss mechanisms in common image compression techniques to preserve focus information rather than visually useful information. So a **third general aspect of this invention** is an image focus assessment method for lossy-compressed images and a lossy image-compression method, wherein the loss mechanism within the compression algorithm is adapted so as to preserve the maximum information useful for focus assessment.

This is particularly useful because lossy image compressors may be more immune to noise fluctuations and instantaneous illumination changes than lossless compressors.

It is further worth noting, that these methods are compatible with single- or multi-region-of-interest focussing systems. In the case of a multi-region-of-interest system, the region with the best discrimination of focus may be selected, or an overall Figure of Merit measurement could be formed by a weighted sum of Figure of Merit measurements in each region.

In a further aspect of this invention we consider the situation where the focussing-motor/actuator displays hysteresis in its drive-signal-input vs focus-control-output characteristic. This is commonly the case, for example, with all piezoelectric actuators, and specifically the case with the Helimorph[®] actuator technology belonging to 1 Ltd and described in several co-owned patents. The hysteresis needs to be specifically allowed for within the focus-control algorithm.

The hysteresis can be thought of as a process which has persistent state (i.e. the behaviour at any moment in time depends on a number (not necessarily constant) of preceding actions).

Suppose the Helimorph actuator has a known 'hysteresis state'. Data can be collected by measuring the focus quality at a number of positions, e.g. by using any of the Figure of Merit determining schemes described above. By resetting the 'hysteresis state' to the known initial condition, it is possible to predict a path which can be followed to return to the best measured position.

In the simplest case, this can be reduced to a full-flyback approach. In Fig. 2 is shown schematically a focus control voltage as a function of time, as might be applied to any sort of focussing motor/actuator and specifically to a PZT actuator which might be a Helimorph actuator:

The focus control procedure which overcomes hysteresis-induced focussing problems and which is **this aspect of the invention** is as follows:

1. Start at any focus position / focus drive voltage within the range of the system;
2. Apply the largest magnitude acceptable negative [positive] voltage (which must be lower than or equal to the hysteresis 'history of commands'; i.e. the actuator/motor must not previously have been subjected to a larger magnitude than this in its operational state);
3. Scan to largest magnitude desired positive [negative] voltage, measuring the focus quality (Figure of Merit) during the scan at as many points as necessary for the accuracy required, or continuously, and noting the focus-drive voltage applied when each focus quality measurement was made;
4. Determine the best focus quality from amongst the set of measurements made and determine the associated focus-control voltage;
5. Apply largest magnitude desired negative [positive] voltage;

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6. Apply the same focus-control voltage at which best focus quality was previously observed.

Note that in step 2 above one can initially slew to either the most positive or most negative allowable drive voltage, and then in step 3 the scan is to the opposite end of the range of allowable focus voltages. Step 5 is chosen positive or negatively accordingly. Where a unipolar drive only (not bipolar) is used, then replace the *maximum negative magnitude* with *smallest magnitude*, and *maximum positive magnitude* with *largest magnitude*, respectively, or vice versa.

The changes in voltage between these steps do not have to be linear, or at the same rate as each other. (For example, a slow, stepped function may be used for measuring the focus at several positions. After this, it is acceptable to flyback at high speed). The key feature of the focussing algorithm to avoid problems due to motor/actuator hysteresis, is that changes in voltage are **monotonic** in each section. Note that this method can be applied more generally to any focus system containing hysteresis in the overall control system (e.g. we have described a system where the hysteresis is specifically in the motor/actuator, in this case because it was made with PZT, but the method works just as well if some or all of the hysteresis is in the motor control system or in the Figure of Merit determining system). All such variants are included in this invention.

A simple 'dual flyback' focussing system as just described can operate very quickly, and in particular, in a usefully short time: consider for example a camera with an F2.8 aperture and a focussing lens with focal length of 4.25mm. For a 3.6um pixel-pitch sensor, we can set the circle of confusion to 10.2um (i.e. the diagonal of a 2x2 pixel block, the smallest all-colour imaging element in a colour sensor). With these constraints, the range of focus from 10cm to infinity can be covered in 4 depth-of-field ranges (centred at 117mm, 169mm, 292mm and 633mm).

To allow for the non-ideal characteristics of the total optical system (gravity, hysteresis, angular tolerance between lens and sensor etc) it would be prudent to allow for 6 depth-of-field ranges. In good light conditions (so that the exposure time is short compared with the frame time), the device movement between adjacent depth-of-field ranges can be completed in the non-exposed portion of one frame when running at 30fps or slower, a frame rate which is common in such cameras. Experiments have shown that a flyback time as small as 15ms works correctly.

Therefore a full "dual-flyback" autofocus cycle can complete in the following time:

$$\begin{aligned}
 &1 \times 15\text{ms (for initial flyback)} + \\
 &6 \times 33\text{ms (to test depth of field ranges)} + \\
 &1 \times 15\text{ms (for final flyback)} + \\
 &1 \times 33\text{ms (to return the optimal frame)} = 261\text{ms}
 \end{aligned}$$

This autofocus cycle time, just over 1/4 second, compares very favourably with many alternative systems.

The Helimorph[®] actuator displays hysteresis because the fundamental material (e.g. PZT) is hysteretic. The material properties can be well controlled in a production situation, and



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therefore look-up tables or brute calculation of hysteresis estimates can be of use to compensate for hysteresis. This is not a complete solution. Perfect hysteresis compensation changes with the environmental conditions of the unit (particularly temperature), the orientation, location of end stops and other physical and mechanical parameters.

However, such "open-loop" compensation by calculation or table look-up can produce a useful 'first guess' at a hysteresis-compensated position for best-focus which can be further refined by a 'hill climbing' algorithm. So *in yet another aspect of the invention*, the autofocus procedure is to perform a scan as described before in steps 1 to 4 to determine at which control voltage focus quality was best (highest Figure of Merit), and then to apply that voltage plus a hysteresis compensation voltage correction, derived by calculation and/or look-up tables, possibly augmented by environmental measurements (e.g. temperature) used in such a way as to fine tune the calculation and/or table look-up.

A further method of finding the optimal focus position is to record the Figure of Merit M at a number of different focus **positions**, and then use a curve-fitting technique to predict the optimal focus position. The curve fit can use a simple arithmetic equation, such as an n^{th} order polynomial, or instead could be chosen as a best-fit to a curve taken from a library of curves pre-measured from representative scenes. There are numerous enhancements which can be made to this scheme:

- Relating position and voltage by some calculation or look-up table as described above.
- In the case where the estimate is taken from an ensemble of representative scenes, then the algorithm can learn over time, appropriate scales and offset values. That is, the physical unit will differ from the reference unit with which the data ensemble was recorded (due to mechanical and material tolerances). The algorithm can develop a model of how the library values map to the actual values required for a particular system.
- Bayes theorem is a powerful tool in this context. The distribution of errors between the 'correct' Figure of Merit for a scene and the measured Figure of Merit (which is perturbed by instantaneous factors such as noise) can be reasonably well estimated. Even in the case of simple 'hill climbing', Bayes Theorem provides a method for distinguishing signal from noise.

Specifically in the case where the focus motor/actuator is based on PZT or other piezoelectric material, another strategy may be used; the actuator control signal used is *charge* instead of *voltage*. When this is done the hysteresis of the piezoelectric material is greatly diminished, i.e. the relationship between device charge and focus position achieved is largely free of hysteresis. All that is necessary is to monitor the charge entering and leaving the piezoelectric actuator instead of monitoring the drive voltage applied to it. So in yet *another aspect of the invention*, the autofocus procedure is to perform a scan cycle (as described above in steps 1 to 4, but with *charge* inserted wherever *voltage* is mentioned) and then to drive the actuator to the charge state wherein best focus quality was measured during the scan, this time without any additional compensation. To a good approximation the same optimal focus will be achieved.

Having positional feedback from an optical system component which can be related to the physical lens position makes the problem of hysteresis easy to solve. A simple controller (PID,

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for example) can be easily used to return the lens to the position of best focus achieved during an initial focus measuring scan as previously described.

In a camera this feedback could be obtained by several means. Strain gauges could be attached or printed onto certain components (such as a supporting hinge or flexure). The Helimorph® actuator electrodes themselves could be made into strain gauges (see for example the co-owned patent no. XXXXXXXX).

Alternatively, a light source could be arranged to reflect off a moving part, or pass through the focussing lens, so as to strike the main image sensor at a position on the sensor directly dependent on the position of the lens along its focus travel. This light source would either have to strike a normally "dark" area of the sensor surround (i.e. an area not used directly for image capture, but in this case, dedicated to focus position sensing), or the light source amplitude can be synchronised to the camera sensor frame rate (so that either you have the light source on for every nth frame only and off in between, or alternatively the light source could be turned on between image captures). Another alternative is to give the light source a particular characteristic which could be easily removed from the image in post-processing.

So *in yet another aspect of the invention*, a positional feedback system measuring a quantity directly related to the position of the focussing element within its range of travel is used to provide a signal to return the focus element to the position of optimal focus as determined by a focus scan process similar to that described above in steps 1 to 4.

Another aspect of autofocus technology is as follows: A focus Figure of Merit can be defined (e.g. see above) and methods and processes can be devised to derive a Figure of Merit for any particular portion of an image however captured by some kind of camera, e.g. again as described above. However, all such methods and processes determine a simple number – a single measure of how good the focus was with that particular set-up. In general, such a Figure of Merit tells how good (or bad) the focus was/is, but does *not* tell which *direction* the focus mechanism has to be adjusted to *improve* the focus / increase the Figure of Merit. As a result, autofocus methods often resort to complete focus scans (with the focus device scanned across its entire range of operation) after which the best focus is determined by some kind of sorting of Figures of Merit, or, hill-climbing measures are used which blindly probe different parts of the focus-adjust/Figure of Merit space and seek a maximum, local or otherwise.

To put this another way, whilst it is generally desirable to be able to make a *closed-loop servo* focus control system, it is in practice difficult to *close* the control loop, as no *signed error signal* is available, as is required in such feedback control systems. All one has is a Figure of Merit, which is essentially unsigned – it contains no information about which way to adjust the loop, just that it needs adjusting. For image sensors where access to image data is available "on-the-fly" (e.g. line by line as the data is read out from the sensor, as for example, was the case with raster-scanned photo-tubes before the advent of semiconductor image sensors), then it is possible to develop some Figure of Merit sign information, as well as magnitude.

Consider a closed loop controller as depicted schematically in simplified form in Fig. 3.



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In this idealised closed loop controller, a lens 3 is moved by an actuator 4 so as to direct light more or less focussed onto an image sensor 1 which in turn produces a video output signal 2 in response to the incident light. The video signal is optionally processed by a Follow & Hold circuit 6 which allows portions of the total image line to be selected for use in determining focus quality (Figure of Merit). The Follow & Hold output is low pass filtered by the Low Pass Filter (LPF) 7 which has a cut off frequency of less than about $F_s/2$, where F_s is the sample rate in pixels/sec emitting from the sensor 1, so as to avoid aliasing. The filtered signal then passes to the High Pass Filter (HPF) 8 which has a gain characteristic rising smoothly and monotonically with frequency from the lowest video frequency to around $F_s/2$ after which it flattens out, so as to emphasise detail in the image. This emphasised signal is then passed to the absolute value stage 9 where it is effectively rectified before being passed to a further LPF 10 with a very low upper-cut-off frequency F_f , where F_f is just high enough to pass a few cycles per line-period (so that focus variation as a function of position in line is measurable). The filtered focus information is then further gated by a 2nd Follow & Hold device 11 which allows selection of a portion only of the vertical field to be selected for focus assessment. The image sensor 1, and the two Follow & Holds 6 & 11 are all timed by a Frame Generator 5 so as to maintain synchronisation. A Loop Controller then drives the Lens Actuator 4 via the Actuator Driver 13, on the basis of the information it receives from the Follow & Hold 11, which may be regarded as an estimate of Figure of Merit, and the timing from Frame Generator 5.

Such a closed loop system as described is difficult to implement because of the lack of sign information in the Figure of Merit signal entering the Loop Controller. In the improved focus closed loop control that is **another aspect of the present invention** a sawtooth (or sawtooth-like, e.g. triangular, or even sinusoidal or even pseudo-random) **dither** signal is generated and added into the focus actuator control signal, to **dither** the focus actuation about its mean position as a function of time as illustrated in Fig.4.

In the modified closed loop focus controller depicted in Fig. 4 the Loop Controller 12 of Fig. 3 has been replaced by a specific implementation of Loop Controller components illustrating a way of overcoming the problem of lack of focus quality sign information previously noted. Two new key components, a Dither Generator 19 and a Phase Sensitive Detector 18 work together to provide information regarding the increase or decrease of focus quality with actuator drive level. The Dither Generator is a nominally free-running oscillator producing a sawtooth or similar waveform (the "Dither" signal) as described above (but rather than being totally free-running it may optionally and perhaps advantageously be synchronized with the Frame Generator 5). Its output, the Dither, is added into the signal to the Actuator Driver 13 via Adder 14, causing whatever motion or static position is demanded by the other Adder input from Polarity Switch 15 to oscillate at a low rate. This in turn causes a small oscillation in lens focal length which imprints this oscillatory change on the Figure of Merit signal produced at the output of Follow & Hold 11. Because only a small oscillation of focus position is caused the deviation caused by this in the Figure of Merit signal will be small compared to the total possible variation of this signal, and the dither signal component will thus be "noisy". However, the Phase Sensitive Detector 18, which is phase locked to the dither generator, can detect the dither component with high noise rejection. When the detected dither signal indicates that small deviations of focus position of one polarity increase the Figure of Merit

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(i.e. better focus) then the PSD 18 produces, say, a positive output, and when the PSD detects that the same polarity of deviation decrease the Figure of Merit then the PSD produces, say, a negative output. In this manner, the dither plus the PSD generate information about which direction the lens focal length needs to be changed (i.e. increase or decrease) to improve focus. The output of the PSD 18 is then used to operate the Polarity Switch 15 which is effectively a unity gain buffer or inverter between the Follow & Hold 11 output (Figure of Merit) and the Adder 14, depending on the PSD input. Thus the control loop has been closed but with selectable loop gain polarity. This is just what is needed to allow continuous closed loop feedback control of the focus adjustment of the Lens 3. A further component, Threshold Detector 16, deriving its input from the Figure of Merit output of Follow & Hold 11, can be added to flag to the rest of the camera-containing system, whenever the focus is "good enough"; i.e. when the figure of Merit has risen above a certain quality threshold. This threshold Output signal 17, can be used, for example, to tell the camera system to "take/Store a picture now". In the system depicted in Fig. 4 Output 17 is also used to control the dither generator 19; for example, the dither can be turned off whenever focus is as good or better than some acceptable limit. Output 17 may also be used to gate Actuator Driver 13 so that it locks the lens position once a certain quality of focus has been achieved. In this way stable images can be captured, as well as electrical power reduction achieved in various of the cameras system components (e.g. focus actuator and driver).

Some or all of the signal processing components depicted in Fig. 4 may be implemented in hardware, and the remainder if any in software. Many variations of this basic theme (i.e. of adding some dither to the lens focal length in order to determine the sign of Figure of Merit change with lens movement) may be implemented in practice and the specific example shown is in no way limiting. So, *in this aspect of the invention* a small amplitude dither signal is imposed on the focal length value of the imaging lens and the dither-synchronous deviation in detectable Figure of Merit used to determine the direction of focal-length change required to improve the focus of the image on the sensor.

Where piezoelectric elements are used as part of the focus control of an optical system, relatively high drive voltages are frequently required to actuate or drive the piezoelectric material, because such materials typically require drive electric fields of between 500V/mm to several thousand volts per millimetre, and because very thin piezo layers (less than say 20 to 60um) are technically difficult to achieve. So for example, a material requiring 1000V/mm drive field and where the layers are 100um thick requires a drive voltage of 100V. In portable and other battery operated equipment such high voltages are generally unavailable and it becomes necessary to generate these voltages from the low battery voltages commonly available (e.g. between 2V and 6V). It further is necessary to control the high voltage drive to the actuator, with some kind of high-voltage amplifier. In mobile-phone or cell-phone applications, (and similarly in PDA, laptop computer, Ipod, and other small battery portable devices) [all hereinafter denoted as "Portable Device"] cost of components, space taken up by components and weight of components are critical items for the acceptance of any devices in these applications. Most standard semiconductor ASIC processes are optimised for low voltage circuitry so it is in practice difficult to integrate the high voltage generator circuitry and/or the high voltage drive amplifier circuitry, within other silicon integrated circuits inside the Portable Device.



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It is therefore ***another aspect of the present invention*** to provide a single small silicon integrated circuit incorporating all the necessary semiconductor elements required for the conversion of a low voltage battery supply (less than 12V, or less than 6V, or even less than 3V or 2V) to a high voltage adequate to supply a high voltage amplifier for driving a piezoelectric actuator device (more than 12V, or more preferably more than 20V, or even more preferably more than 40V or even more than 75V) and integrated together in the same silicon ASIC all the semiconductor elements required to provide the high-voltage amplification required to directly drive the piezoelectric element, such a composite voltage step-up and amplifier/controller being optimised for very low power consumption (less than 250mW or preferably less than 100mW or more preferably still less than 50mW or even less than 20mW) and very small package size (less than 10mm square or preferably less than 5mm square or more preferably less than 3mm square or even less than 2 or 1mm square).





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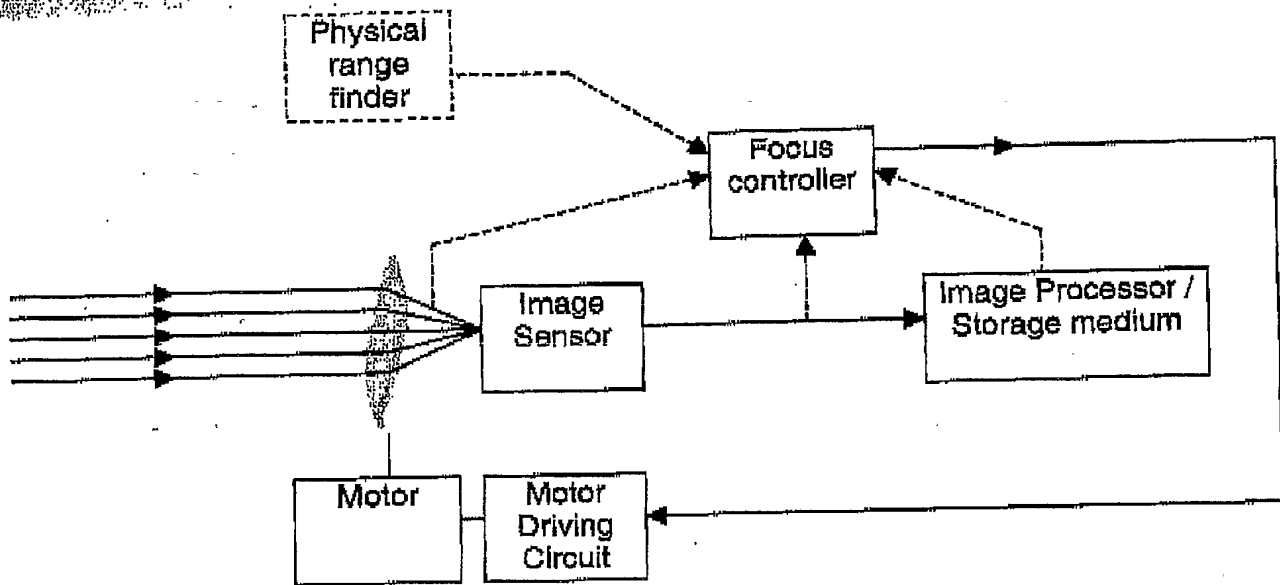


Fig.1.

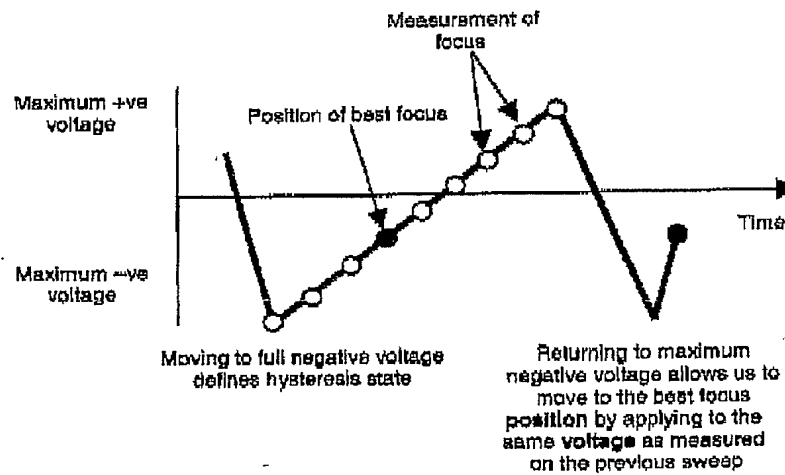


Fig. 2



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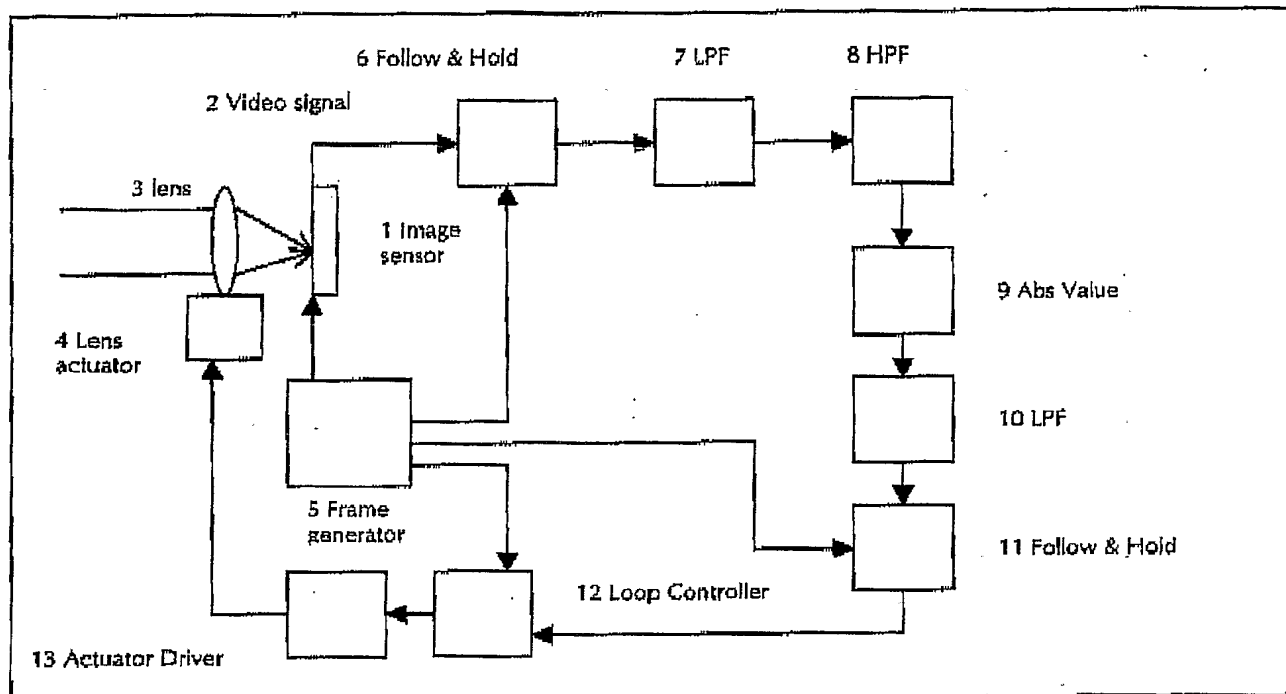


Fig. 3



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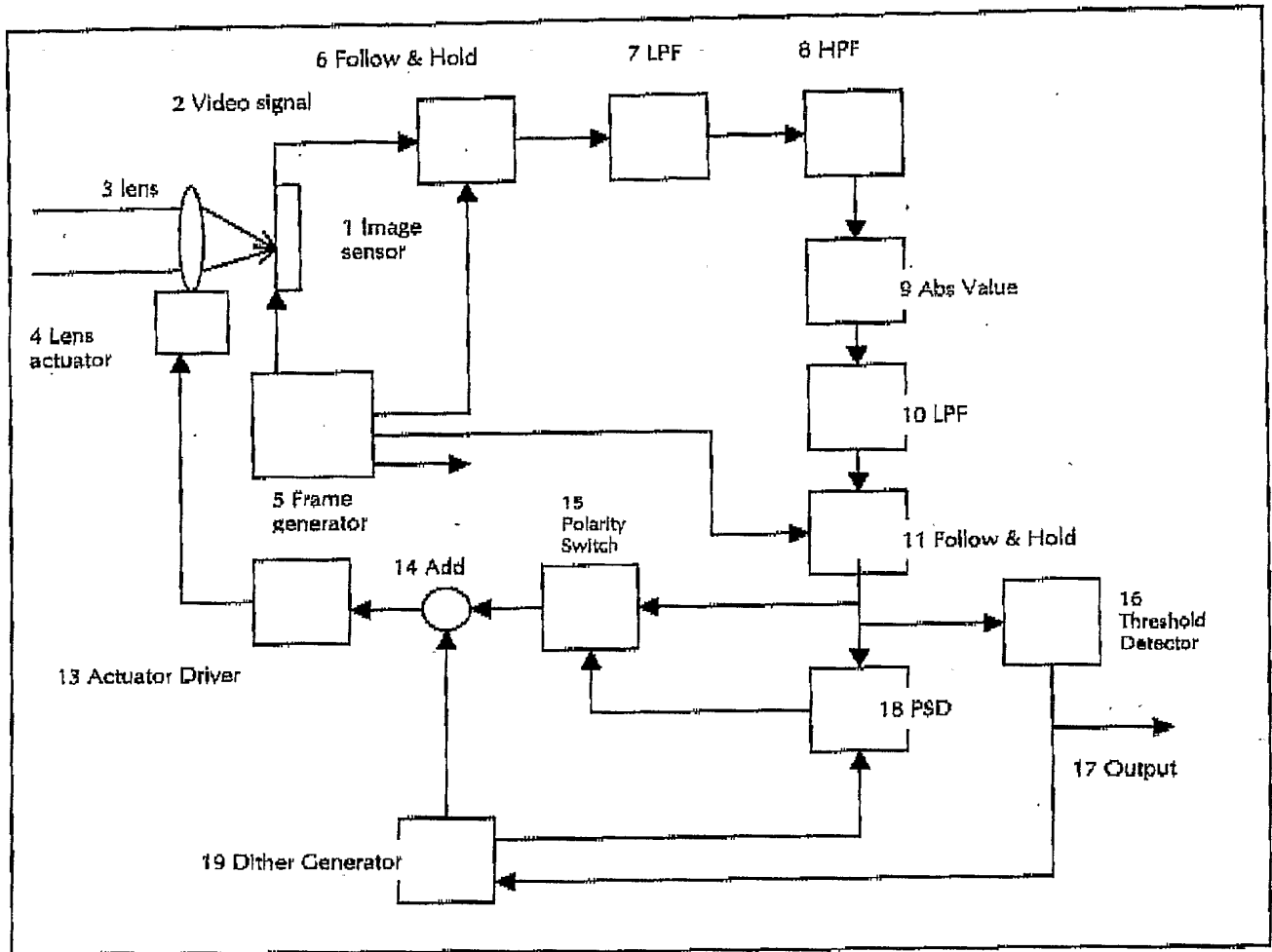


Fig. 4

